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EXECUTIVE SUMMARY OF THE THESIS

Evaluating Mechanical and Thermal Properties of MDO PE and BOPP Films for Enhanced Food Packaging Performance

TESI MAGISTRALE IN FOOD ENGINEERING

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1. Company

Goglio S.p.A. is an Italian company specializing in packaging solutions, particularly flexible packaging and packaging machinery. Founded in the early 20th century in Lombardy, Italy. Goglio's product range includes flexible packaging solutions like bags and pouches used for various food products, including coffee, snacks, pet food, and more. They are particularly renowned for their expertise in coffee packaging, offering solutions like coffee valve bags that preserve the freshness of coffee beans and ground coffee. Additionally, they specialize in producing high-barrier laminates used in various packaging formats such as vacuum packs, soft packs, stand-up bags, and industrial bags on reels [1].

2. Objective

The objective of the work is to determine the mechanical properties, particularly the elastic modulus, of plastic films focusing on MDO PE (machine-direction oriented polypropylene) films, at different operating temperatures within the plant. The goal is to establish a range of energy per unit area $[\frac{J}{m^2}]$ that can be applied to the film during the solvent removal phase in the drying tunnel compatible with the desired solvent retention and tension needed on the film during production to guarantee the quality of the final product. This will ensure that the plastic material is acceptably deformed in the machine direction following production quality standards. The MDO PE layer is supposed to be used in a multilayer packaging solution.

3. Converting process

To better understand the objective of the thesis, it's important to have a clear understanding of the phases through which a film is subjected in order to produce a multilaminate. More specifically, keeping in mind the objective of the work, it's crucial to delve into the lamination phase, which is the moment when the different plastic layers are joined together to produce the finished product. In order for the film to be manipulated, it is necessary to apply tension to the material (in machine direction). This is achieved through the use of NIP points, where the film is "pinched" between two rollers, a rubber roller, and a motorized cylinder. Each NIP point controls the tension of the material in that specific sector, and the tension is detected and adjusted using dancers and load cells. To be laminated, the film is sprinkled with a solvent-based adhesive, more specifically ethyl acetate, after which it passes through a drying tunnel so that the solvent can evaporate and be recovered. The evaporation of the solvent is a crucial phase in the lamination process as it involves applying a pull on the film and simultaneously applying heat. Perfect management of the drying tunnel allows enough solvent to evaporate in order to pass quality tests without excessively heating the material, risking compromising its elastic properties and thus causing deformations in the machine direction (MD) that could make the finished product inadequate [2]. Of the mechanical characteristics, the Young's modulus (in the machine direction) represents one of the most important values, as it provides information on how much the material will elongate knowing the applied stress [MPa] and the initial length.

4. Materials tested

In this section, a brief overview of the tested materials.

4.1. MDO PE

MDO PE film, or Machine Direction Oriented Polyethylene film, is a type of plastic film that is produced by a specialized manufacturing process to enhance its physical properties. This film is primarily made from polyethylene, a commonly used polymer in the packaging industry [3].

4.2. BOPP

The starting point of Biaxially oriented polypropylene (BOPP) films is polypropylene polymer which is manufactured through the process of addition polymerization. Biaxial orientation enhances the film's properties, including increased tensile strength, heightened stiffness, improved clarity, enhanced resistance to water vapor and oxygen permeation [4].

4.3. Film selected

The work focuses on five types of MDO PE films supplied by different companies (listed as named by the managerial software used in the company):

- PEMDOTT (in use by Goglio S.p.A.)
- EXC21011
- EXC23453
- EXC21004
- EXC21008

Additionally, a decision was made to test also a BOPP already widely used in the company:

- MOPOTT

5. Tensile test

To describe the behavior of Young's modulus with varying temperatures, several hot tensile tests were conducted. Analyzing data on operating temperatures in production and the melting points of materials derived from DSC analysis, it was decided to perform 3 sets of hot tensile tests (in the laboratories of the Politecnico di Milano) at 30, 60, 80°C to obtain representative data of the film temperature outside the oven (30°C), inside the oven (60°C), and in a worst-case scenario (80°C). Furthermore, a second round of tensile tests at room temperature (in the laboratories of Goglio S.p.A) was carried out to provide data to ensure the reliability of the results obtained from the hot tensile tests and to validate the models subsequently developed. Test were performed following ASTM D882 – 10. Where it was not possible to follow the standard, the validity of the data used was demonstrated with subsequent tests.

6. Results of the test

The results shows that the disparity in the Young's modulus values of different materials becomes less pronounced with an increase in the operating temperature and as one might expect, an increase in the material's temperature is correlated with a decrease in Young's modulus.

In terms of specific materials, there are notable differences in performance. For example, the MDO PE material labelled as EXC21008 consistently shows inferior properties compared to its counterparts across the range of temperatures tested. This could indicate a fundamental difference in the composition or manufacturing process of EXC21008, leading to its lower performance. On the other hand, when focusing on the tests conducted at 60°C, which align closely with real-world operating conditions, EXC21011 emerges as the better MDO PE material, demonstrating the highest Young's modulus. This is closely followed by EX23453 and EXC22004. The high performance of EXC21011 could be attributed to its material composition, processing methods, or other factors that contribute to its enhanced elastic properties. It is worth mentioning that the variations of Young’s modulus are quite similar for all MDO PE materials, especially the final drop from 30°C to 80°C, which is close to -74% for all materials. This result could be anticipated, considering the comparison is among very similar materials. However, this trend is also confirmed by MOPOTT, a BOPP material, which also exhibits a change in Young's modulus from 30°C to 80°C of -75%, despite not being an MDO PE. These results could indicate that the change in Young's modulus due to temperature variation might be similar even among plastic materials not belonging to the same family, like MDO PE and BOPP. Although further studies are required to confirm this hypothesis.

Tensile tests were also conducted at different grip separation speeds, leading to the conclusion that a higher speed is associated with an increase in the elastic modulus. More specifically, starting from a speed of 25 $[\frac{mm}{min}]$ and reaching 250 $[\frac{mm}{min}]$, an average increase in Young's modulus across all the MDO PE of 22% was recorded.

7. Models developed

By interpolating the data on Young's moduli at temperatures of 30, 60, and 80°C, an exponential model was constructed for each material, capable of predicting the Young's modulus at any operating temperature, not just those at which the tests were conducted. The fourth set of data on Young's moduli recorded at a temperature of 24°C was used to validate the proposed models and thus understand their actual effectiveness. The software use was Microsoft Excel® as one of the most used software in the company The models are showed in the following table.

Table 7.1 exponential models developed

	Exponential model	R^2
pemdott MD	$2039.4e^{-0,028T}$	0.9928
EXC21011 MD	$2580.8e^{-0,03T}$	0.9984
EX23453 MD	$2258.5e^{-0,027T}$	0.9936
EXC22004 MD	$2203.4e^{-0,028T}$	0.9982
EXC21008 MD	$1528.7e^{-0,024T}$	0.9940
mopott MD	$5842.8e^{-0,027T}$	0.9878

Where T represent the temperature in [°C] and the output is the Young’s modulus in [MPa].
As can be seen from the R-squared values, the interpolation fits very well to the initial data. Moreover, after the validation phase, it was concluded that these models act as a valuable starting point for predicting material elastic behavior under temperature variations for both MDO PE and BOPP materials. Finally, knowing that the maximum acceptable deformation is 2mm per meter, it is possible to calculate the maximum force applicable to the film using the following equation:

$$F = E * \varepsilon * A_{cross\ sectional} \qquad 7.1)$$

Where:

- F is the force pulling the film in [N]
- E is Young’s modulus calculated with the models above in [MPa]
- ε is 2*10^(-3)

8. Thermal properties MDO PE e BOPP

To describe what happens inside the drying tunnel, it's important to better define the thermal properties of the MDO PE and BOPP films being tested. A key value for this analysis is the specific heat. Laboratory analyses were conducted to detect how and by how much the specific heat value varied depending on temperature. Analyzing the results, a linear variation between specific heat capacity $[\frac{J}{g°C}]$ and temperature [°C] was observed for all the materials tested within the temperature range used in production, specifically 20-100°C. In this case a linear interpolation was performed to create a model that allowed for precise determination of the specific heat at all production temperatures. Below is the table with all the derived models.

Table 7.2 linear models of Cp obtained by interpolation of data regarding the value of Cp(T) in different temperature condition from 20-100°C

	Cp(T) model	R^2
pemdott	0.0188T+1.9088	0.9854
EXC21011	0.0189T+1.85	0.9885
EXC23453	0.019T+2.4645	0.9931
EXC22004	0.0152T+1.326	0.9859
EXC22008	0.0236T+2.6854	0.9650
mopott 21008	0.0128T+2.1296	0.9943

As can be seen from the R-squared values obtained, all the linear models represent very accurately the behaviour of specific heat capacity with temperature variations in the production operating range of 20-100°C. Since the relationship is linear, a simple average between the Cp at initial temperature and Cp at final temperature provides an extremely representative mean value.

9. Solvent evaporation and energy needed

Finally a very important aspect concerns the evaporation of the solvent. Indeed, part of the energy supplied by the drying tunnel is used to increase the temperature of the material, and part is absorbed by the solvent as it transitions from the liquid to the gaseous phase. Accurately describing the solvent's transition process from liquid to gaseous phase would be extremely challenging. This is because, being a highly volatile compound, it spontaneously tends to diffuse into the gaseous phase at room temperature. Additionally, a detailed investigation into the direction, flow, and speed of the air jets within the drying tunnel would be required. Furthermore, for different types of laminates, the grammage of the material varies, thus changing the quantity of adhesive per square meter applied, the desired operating temperatures, and the necessary solvent retention to pass quality tests. As a first approximation, it is possible to quantify the amount of heat absorbed by a material and the solvent by using the following equation:

$$Q = mc_p\Delta T \tag{9.1}$$

Where:

- m represents the mass of the material measured in [g]
- c_p is the specific heat capacity measured in $[\frac{J}{g°C}]$ and it's dependent mostly by the temperature of the systemc
- ΔT is the change in temperature due to heat transfer [K]

Assuming a grammage of 20 $[\frac{g}{m^2}]$ with complete evaporation of the solvent (hence zero solvent retention), a film temperature inside the tunnel of 65°C and a starting one of 20°C, a constant specific heat of ethyl acetate at 168.94 $[\frac{J}{mol*K}]$ [5] and a molar mass (MM) of 88.10 $[\frac{g}{mol}]$. Using the same model proposed for equation 9.1, we would arrive at a result of 1735.83 $[\frac{J}{m^2}]$ for the evaporation of the solvent. Meanwhile, to heat the plastic material (starting also from 20°C to 65°C), using supplier data regarding density of 0.94 g/cm³, a thickness of 0.000030m, and an average specific heat for the PEMDOTT (using equation from table 7.2) at 2.7078 $[\frac{J}{g°C}]$, the necessary energy is calculated as 3436,2 $[\frac{J}{m^2}]$.

The total energy, summing up that required for evaporating the solvent and heating the plastic film, would amount to 5190 $[\frac{J}{m^2}]$.

It is important to emphasize that this represents an incredibly simplified scenario. This simplified model provides a basic framework to understand the energy requirements for processes like solvent evaporation and film heating. However, in real-world applications, numerous other factors come into play. The actual energy consumption and process efficiency could differ significantly from the predictions of this basic model.

10. Conclusion

This thesis thoroughly investigates the mechanical and thermal properties of MDO PE and BOPP films, utilizing extensive testing at various temperatures. Key findings include the development of exponential models to predict changes in Young's modulus with temperature, aiding in understanding the films' elastic

properties. Also the results from the tensile tests have been instrumental in supplier selection, guiding decisions based on the mechanical properties of materials from different suppliers. The work also introduces a simple yet effective model for calculating specific heat capacity, based on temperature dependency. Created using Microsoft Excel®, these models are practical and user-friendly. The work also suggests future improvements for enhanced reliability, particularly for materials like PEMDOTT. Overall, the thesis provides valuable tools and insights for the industrial application of these films, with potential for further refinement and broader applicability.

References

[1] Goglio S.p.A., "History," 2023. [Online].

[2] Goglio S.p.A., "Internal documentation," 2023.

[3] S. T. W. S. L. Silvia, "Study of the water absorption and its influence on the Young's modulus," *Polymer testing* , 2013.

[4] J. J. R. Wagner, "MULTILAYER FLEXIBLE PACKAGING, PLASTICS DESIGN LIBRARY," 2016.

[5] R. B. M. P. M. P. A. G. R.-D. e. J.-P. G. M. Baluja, "Unusual dependence on concentration of the excess heat capacities of ester solutions in alkanes".

[6] "https://support.microsoft.com/en-us/word," [Online].

[7] D. Alighieri, Comedia, Firenze: Goose Feather Press, 1321.

[8] J. Watson, F. Cric, "Molecular structure of nucleic acids: a structure for deoxyrobose nucleic acid," *Nature,* vol. 171, p. 737–738, 1953.

[9] Prometeus, "Fire". Olympus Patent 1, 300.000 BC.

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